Mechanical Performance of Neutron-Irradiated Dissimilar Transition Joints of Aluminum Alloy 6061-T6 and 304L Stainless Steel

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Abstract

Bimetallic transition joints using aluminum alloy 6061-T6 and stainless steel 304L are useful in providing reliable stainless steel welds on nuclear components at temperatures below 200°C, while maintaining the attractive radiation tolerance of the aluminum alloy. The mechanical performance of inertia welded Al6061-T6:SS304L transition joints was evaluated after neutron irradiation up to 3.45 dpa at 100°C (maximum) in the High Flux Isotope Reactor to determine the viability of using these transition joints for nuclear and reactor applications. Neutron radiation produced moderate hardening ($\Delta\sigma_y \approx$ 90 MPa) with limited change in ductility. Tensile specimens were produced from multiple transition joints and no batch-to-batch variation was found. Tensile responses were found to align with typical responses of wrought Al6061-T6, indicating that the behavior of the joints was dictated by the Al6061-T6 section of the joint.

Keywords: Weld; Bi-metallic transition; 6061; Radiation Tolerance

1. Introduction

Joining of dissimilar metals through friction welding, specifically inertia welding, has been used since the early 1990s and has a wide array of industrial applications, including automotive, aerospace, shipbuilding, and so on. [1–4]. It is one of the many solid-state weld processes that have been applied to create bimetallic transition joints between aluminum (Al) and stainless steel, including impact welding [5], explosion welding [6], and ultrasonic welding [7], among others [8]. In conventional fusion welding processes, dissimilar metal joining is complicated by differences in melting points and thermal mismatch; solid state welding can mitigate these effects because the weld does not require melting the base metals [9].

Bimetallic welds are far from novel in the nuclear industry and are widely used to join carbon steel or low-alloy pipes to austenitic parts used in high-temperature regions where increased creep strength and oxidation resistance are essential [10–12]. However, these bimetallic welds are typically limited to fusion welds with a buttering layer. Recently, friction stir welds have been studied for welding advanced nuclear fuels and oxide-dispersion-strengthened alloys and for fuel plate fabrication [13–15].

Generally, a friction weld is achieved by bringing two pieces into contact and using the relative motion between the two to generate frictional heat, which bonds them. It is typically performed by rotating one piece while the other is held fixed. The rotating piece is pressed onto the fixed part and the friction creates heat, which fuses the two workpieces; but it does so at a lower temperature than the melting temperature [16]. Because the pieces do not melt, this process is especially advantageous for welding dissimilar metals in which thermomechanical properties may differ—a task that is difficult or impossible for conventional fusion welding [17]. Note that inertia welding is a subset of the friction weld process that uses specific equipment, such as a flywheel and clutch, to impart the rotational energy along with specific process controls.

Inertia welded bimetallic joints are of particular interest for use in irradiation capsules for materials testing reactors, including the High Flux Isotope Reactor (HFIR) at Oak Ridge National Laboratory (ORNL). The Al alloy Al6061-T6 is of primary interest for use as irradiation capsule components in materials test reactors because of its radiation tolerance even at low temperatures and its compatibility with the primary coolant used in HFIR [18]. However, fusion welding with Al/Al alloys introduces several difficulties, including oxide layer formation, hydrogen solubility in the liquid state, and solidification cracking [19]. Additionally, the material properties of Al-based alloys—such as the low melting point, high thermal conductivity, and high thermal expansion—further complicate the process. Furthermore, irradiation vessels that are designed and fabricated to contain activated specimens tend to be very expensive and generally do not easily bear the cost and risk associated with such precarious weld processes. For such vessels, the closure welds, which provide some structure and hermetic seals, must be completed in a remote handling radiological facility or glove box to reduce radioactive exposure to personnel. Generally, the interfaces for such environments include mechanical master slave manipulators or cumbersome glove ports that limit dexterity as well as operator visibility. The use of Al6061-T6 to SS304L transition joints will allow for tungsten inert gas welding of the austenitic 304L stainless steel (SS304L), which is generally more reliable to weld than Al6061-T6 and negates many of the issues described for Al/Al weld joints. Ultimately, the goal is to minimize risk and fabrication-associated difficulties by transitioning toward Al6061-T6 components inertia welded to SS304L.

Currently, there is a lack of irradiation performance data related to the mechanical properties of irradiated Al6061-T6 to SS304L transition joints. Up to now, work has been conducted to evaluate the mechanical properties of unirradiated Al6061-T6 to SS304L joints [20,21], while experiments on irradiated joints have been focused on microstructural characterization and corrosion. It has been claimed that the transition joint is limited by the Al6061 yield strength, which is reduced by the heat-affected zone produced during the inertia welding process. Additionally, irradiation has not been shown to induce any significant changes in strength and ductility [20,21]. However, no database currently exists on the mechanical properties of these transition joints as a function of irradiation damage.

While Al6061-T6 to SS304L transition joints have been used in the past, the transition joints were in regions of relatively low radiation dose [22]. In irradiation capsules, where damage doses can exceed tens of displacements per atom (dpa), the strength of the weld is especially important to prevent capsule failure and possible reactor coolant ingress. There is a clear need to understand the irradiation performance of bimetallic joints and develop the necessary mechanical properties database before dissimilar transition joints can be used in high-neutron-dose environments. This work details the initial experiments performed to assess the mechanical properties of Al6061-T6 to SS304L (Al6061-T6:SS304L) transition joints after neutron irradiation in the HFIR.

2. Materials and Methods

The bimetallic joints used in this work were manufactured commercially by Interface Welding (https://www.interfacewelding.com/), part no. IWAL/SS-15 Rev. "A," and processed according to MIL-STD-1252 [23]. The bimetallic joint was fabricated from solid rod; the Al6061-T6 portion having and outer diameter of 1.91 cm (0.750 in.) and the SS304L portion having an outer diameter of 1.59 cm (0.625 in.). This produces a fay surface area of 1.77 cm^2 and 1.23 cm^2 for the Al6061-T6 and SS304L respectively, and a fay surface areas ratio of 1.44 (not accounting for flash trap). The latter value is greater than 1 and coincides with MIL-STD-1252 specifications for parts that are made from dissimilar materials. Interface Welding used commercially available rod stock, as detailed in Table 1 and Table 2**Error! Reference source not found.**. This transition joint is classified as Type II Class A, because it the rod interface has a center relief (or flash trap) in the SS304L fay surface. As such, the weld interface is not completely free of unwelded area.

The post-weld geometry is shown in the inset images in Fig. 1, where the dark gray material is the SS304L section and the lighter gray section is the Al6061-T6. Note that the center of the joint has unbonded Al6061-T6 extruded into the flash trap. Also, it is believed no post weld heat treatment was performed on the bimetallic weld joint because a reduction in yield stress in the Al6061-T6 was observed which indicates some annealing in the softer base metal in the weld heat affected zone, as discussed later. Other welding parameters, such as spindle velocity, thrust load, inertial mass, and cleaning preparation are not available due to the propriety nature of the commercial production of the test components.

Optical imaging was conducted on metallographically prepared joints, seen in Fig. 1, to show the bond line between the two metals for representative transition joints produced by the manufacturer. The bond line between the dissimilar metals exhibits a periodic shape, which was present in all usable transition joints, and seems to indicate good bonding at the interface. Also, scanning electron microscopy characterization was performed on these sections, and the results did not indicate the formation of any defects or intermetallic compounds at the interface.

Joints for neutron irradiation were machined by wire electric discharge machining to produce dog-bone, sheet type SS-J3 specimens (gauge size 5.0×1.2×0.75 mm) [24]. Machined specimens were loaded into perforated capsules to allow for direct contact with the reactor coolant, resulting in an estimated design temperature of 80–100°C. The irradiation and post-irradiation tensile testing included two unirradiated specimens used as the control, and a minimum of three irradiated bimetal joint specimens from two separate transition joints (designated as Joint A and Joint B). The samples were loaded into peripheral target tube positions with a nominal neutron flux of 1.2×10^{15} n/cm^{2}s (E>0.1 MeV) and total fluence of 2.7×10^{21} n/cm^2 (E>0.1 MeV). Note that for a compound object with dissimilar materials, the damage dose will be different within each material; hence a single, uniform dose per specimen does not exist. For example, the nominal irradiation dose within the base Al6061-T6 was determined as 3.45 dpa and in the base SS304L as 2.04 dpa. In this study, the Al6061-T6 nominal dpa was selected as the nominal dpa of the entire specimen—both for simplicity and, as will be shown and discussed later, because Al6061-T6 was the material controlling the behavior of the weldments under irradiation.

Tensile tests on the SS-J3 specimens in the as-received and irradiated states were performed in a remote handling radiological facility on an Instron universal test machine at ambient room-temperature conditions. Tests were completed using shoulder loading with a crosshead speed of 0.33 mm/min resulting in a nominal strain rate of ~10^{-3} s^{-1}. Owing to the unavailability of a contact or noncontact extensometer at the time of the test, all engineering strains were determined from the digitally recorded crosshead separation. Engineering stress was calculated based on the digitally recorded load and measured thickness and width of the gauge region before the irradiation experiment. Error was reported based on one standard deviation of the mean of the multiple tests for a given joint before or after irradiation.

Fractured tensile surfaces were investigated using a JEOL JSM-6010LA scanning electron microscope (SEM) located in a remote handling radiological facility. Unirradiated specimens were investigated using the same equipment and techniques. The SEM was operated at 5 kV with a 10 mm working distance. When available, both halves of the fractured specimens were imaged in this manner. Fractured tensile specimens were also imaged using a low-magnification USB-powered optical microscope to determine the location of the fracture along the gauge section of the tensile specimens and to determine the general quality of the specimens post-irradiation. Also, when available, both halves of the fractured specimens were imaged in this manner.

3. Results

Representative tensile curves for the unirradiated and irradiated Al6061-T6:SS304L joints are shown in Fig. 2(a), and optical images of the specimens post-rupture are shown in Fig. 2(b). The unirradiated joints showed pronounced uniform plastic deformation followed by necking and fracture within the Al6061-T6 portion of a Al6061-T6:SS304L transition joint. The general values for the strength and ductility of the unirradiated joints (Table 3) were consistent with expected values based on the behavior being controlled within the Al6061-T6 portion of a Al6061-T6:SS304L transition joint (Table 2). Note that the strengths in Table 3 for the unirradiated joints are lower than for typical wrought Al6061 alloys with T6 temper (see Table 2). This result is likely due to thermal annealing of the Al6061-T6 located within the heat-affected zone of the transition joint. The tensile properties of the joints being controlled within the Al6061-T6 section of the joint were further supported by the optical images in Fig. 2(b), which show the failure rupture to be contained within the Al6061-T6 section of the joint. The unirradiated joints all failed in a ductile-like manner, based on the ductility values and the SEM-based fractography shown in Fig. 3. Fracture surfaces show dimple-cone fractures typical of ductile fractures.

Neutron irradiation resulted in a marked increase in the yield strength and ultimate tensile strength of the joints (Fig. 2(a) and Table 3). However, the general shapes and hence the deformation modes of the irradiated joints remained unchanged compared with the unirradiated joints; the uniform and total elongation values were within a reasonable approximation of each other for all conditions studied. The irradiated joints also show the same fracture surfaces with dimple-cone morphologies (Fig. 3). Optical images of the ruptured specimens (Fig. 2(b)) show failure contained within the Al6061-T6 section of the joint, suggesting that after neutron irradiation, the properties of the Al6061-T6 section were still controlling the strength and ductility of the Al6061-T6:SS304L transition joints. Tensile testing of the two different joint batches (A and B) showed no significant differences in the strength or ductility values, indicating limited to no batch-to-batch variability in the radiation tolerance of Al6061-T6:SS304L inertia weld joints.

The inset in Fig. 2(a) also shows continuous serrated flow after yield for the Al6061-T6:SS304L joints in both the unirradiated and irradiated conditions. The observed serrated flow is indicative of the Portevin-Le Chatelier (PLC) effect, which is typical for Al-based alloys [25,26]. The general appearance of the serrated flow was not strongly affected by the low-dose, low-temperature neutron irradiation. This is contradictory to the results of Farrell [27], which showed that mild serration was reduced or completely eliminated for wrought Al5052-0 alloys after high-dose, low-temperature neutron irradiation. The PLC effect strongly depends on the test temperature and strain rate, both of which varied between this study and that of Farrell. It is probable that these factors, as well as the difference between the materials tested (i.e., friction weld joint and wrought material, base composition, and temper) all contributed to the variance in the PLC response after neutron irradiation.

4. Discussion

The unirradiated mechanical properties of the Al6061-T6:SS304L joints shown in Table 3 are lower than those quoted for both SS304L and Al6061 in the T6 temper condition, as shown in Table 2. The observed reduction is not unusual; for example, inertia welds of Al6061-T6 to Al6061-T6 have previously been shown to produce joints with reduced strength compared with their base metal counterparts [28,29]. Transition joints formed between different Al alloys and 300-series stainless steels have also shown the same behavior as that observed in this study [30,31]. For both cases, similar or dissimilar transition joints, the tensile properties of the weld are strongly dictated by the welding parameters. In this study, the welding was carried out by an outside vendor, Interface Welding, and extensive welding trials and optimization of the tensile properties were not within the scope of the work. For the joints studied in this work, it is assumed the reduction in tensile properties compared with the wrought materials is the result of thermal annealing during the weld process, similar to that shown previously by Yokoyama [30] for inertia-welded Al6061-T6:SS304L joints.

For any dissimilar weld, a primary factor for consideration is what material within the weldment/joint or if the joint itself will dictate the mechanical response after irradiation. Herein, we investigate the radiation response of the bulk materials to determine whether the results for the Al6061-T6 portion of the joint, it being the weaker of the two bulk materials, controls the radiation tolerance of the bimetallic transition. Fig. 4 shows the strength and ductility of the inertia-welded Al6061-T6:SS304L joints, compared with those of the wrought 300-series stainless steels and wrought Al6061-T6, as a function of irradiation dose when neutron irradiations were carried out at or below 100°C. Fig. 4 indicates that the tensile properties of 300-series stainless steels changed rapidly at up to ~10 dpa when the different reactor conditions and materials are considered, whereas the changes in Al6061-T6 properties were delayed in comparison—no significant changes were observed below ~1–10 dpa for Al6061-T6. In this study, the yield and ultimate tensile strengths of the inertia-welded Al6061-T6:SS304L joints, as well as their relative changes, were in agreement with the values expected for wrought Al6061-T6. The ductility values were also in agreement with those for both wrought 300-series stainless steels and wrought Al6061-T6; but the change in the values was only minor, suggesting the Al6061-T6:SS304L joint ductility values are more in agreement with the trends for wrought Al6061-T6—a conclusion identical to the conclusion regarding the strength parameters.

The general location of the fracture within the Al6061-T6 (Fig. 2(a)), and the alignment of the strength and ductility values expected for Al6061-T6 based on Fig. 4, further support the observation that the behavior of the inertia-welded Al6061-T6:SS304L joints was controlled by the radiation tolerance of the Al6061-T6 section of the joint. This observation is in agreement with the work of Dunn et al. on inertia welds of Al6061-T6:SS304L irradiated in a spallation neutron spectrum [21]. For practical purposes, within the typical dose ranges under consideration for irradiation capsules in materials test reactors, only the radiation tolerance of Al6061-T6 needs to be strongly considered. But that holds true only if the fracture stress of the base 300-series alloy does not decrease to values similar to those for the yield stress of the Al6061-T6.

Extensive testing of Al6061-T6 has shown that its radiation tolerance and hence its mechanical properties are strongly controlled by the transmutation-produced silicon resulting from irradiation by thermal neutrons. There is only a limited effect due to displacement damage for irradiations below 100°C [18]. The limited effect of the displacement damage is due to the relatively high homologous temperature above ~50°C, which leads to annealing of displacement damage defects. The intrinsic radiation tolerance of Al6061-T6 suggests that inertia-welded joints of Al6061-T6:SS304L should exhibit limited to no radiation hardening and/or embrittlement at low does (<1 dpa); and even at elevated doses, the joints are predicted to show only moderate hardening and minor embrittlement (loss of total ductility) at irradiation temperatures above room temperature but below 100°C. This effect was demonstrated in this study on two different joints irradiated at ~100°C up to 3.45 dpa. Finally, the limited testing shows no batch-to-batch variability in the radiation tolerance of inertia-welded Al6061-T6:SS304L joints, suggesting repeatability from part to part in service applications.

5. Conclusions

Inertia-welded Al6061-T6:SS304L joints produced by a commercial manufacturer were irradiated in the HFIR at 100°C up to a nominal dose of 3.45 dpa to evaluate the mechanical performance of the joints. Results showed that the Al6061-T6:SS304L joints have good radiation tolerance with moderate increases in strength (yield and ultimate tensile) and limited to no change in ductility. The radiation tolerance was dominated by the response of the Al6061-T6 section of the joint. Based on these results, it can be concluded that inertia welding is a suitable welding technology to produce Al6061-T6:SS304L joints for irradiation capsules for materials test reactors. Additionally, it can be suggested that the primary driving factor for degradation of the joint is the radiation tolerance of Al6061-T6 within the conditions studied here.

Acknowledgments

Neutron irradiation of the bimetallic transition joints at ORNL's HFIR user facility was sponsored by the ORNL plutonium-238 production program, which is funded by a joint venture between the Department of Energy and the National Aeronautics and Space Administration. The authors thank Dr. J. Burns for performing the dpa calculations of the irradiated samples, Drs. M. Gussev and L. Tan for their technical review of the pre-submitted manuscript, and Mrs. D. Counce for her assistance in preparing the final manuscript.

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Tables

Table 1: Chemical composition data for the raw materials used for the fabricated Al6061-T6:SS304L joints. Reported values include all chemical components greater than 0.05 wt %.

Material	Spec.	Heat/Lot Number	Chemical Composition wt % (min/max)								
Al6061	ASTM-B221-02	111	Al	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
			Bal.	0.40/ 0.80	0.70	0.15/ 0.40	0.15	0.8/ 1.2	0.04/ 0.35	0.25	0.15
SS304L	ASTM-A276-04	151204	Fe	Cr	Ni	Mn	Si	Cu	Mo	Co	N
			Bal.	18.28	8.42	1.71	0.60	0.42	0.34	0.14	0.07

Table 2: Mechanical properties data for the raw materials used for the fabricated Al6061-T6:SS304L joints.

Material	Specification	Heat/Lot Number	Mechanical Properties		
			Yield Strength (MPa)	Tensile Strength (MPa)	Total Elongation (%)
Al6061	ASTM-B221-02 [32]	111	298	325	15.5
SS304L	ASTM-A276-04 [33]	151204	323	576	51.1

Table 3: Compilation of mechanical properties of inertia-welded Al6061-T6:SS304L joints before and after neutron irradiation. Reported values represent the mean of multiple tests and the reported error is one standard deviation of the mean.

Sample	Condition	T_{test} (°C)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Uniform Elongation (%)	Total Elongation (%)
Control	Unirradiated	24	205 ± 1	252 ± 2	3.4 ± 0.1	7.7 ± 0.1
Joint A	3.45 dpa | 80–100°C	24	305 ± 34	329 ± 38	2.9 ± 0.6	8.0 ± 2.3
Joint B	3.45 dpa | 80–100°C	24	289 ± 6	324 ± 6	3.7 ± 0.3	8.6 ± 0.6

Figures

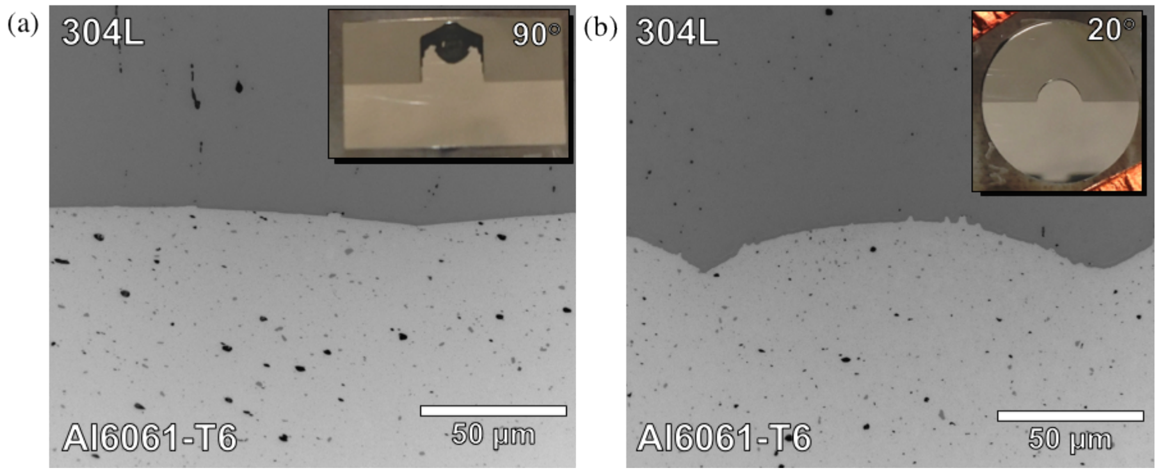

Fig. 1: Optical images showing the interface for transition joints sectioned at 90° (a) and 20° (b) to the bond line. Insets show general bond geometry.

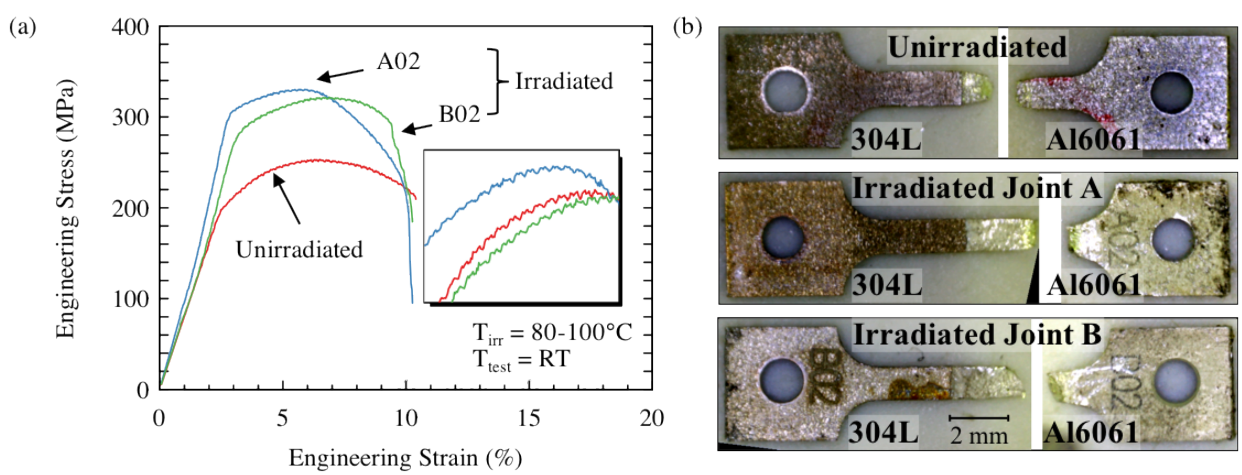

Fig. 2: Representative engineering stress-strain curves of inertia-welded Al6061-T6:SS304L joints before and after neutron irradiation to 3.45 dpa; inset, unirradiated curve shifted up on the y-axis to highlight the magnitude of serrated flow for all conditions in a single inset at strain levels between 3% and 7% (a). Optical images of the fracture morphology of representative tensile specimens post-fracture (b). T_{irr}, irradiation temperature; T_{test}, tensile test temperature; RT, room temperature.

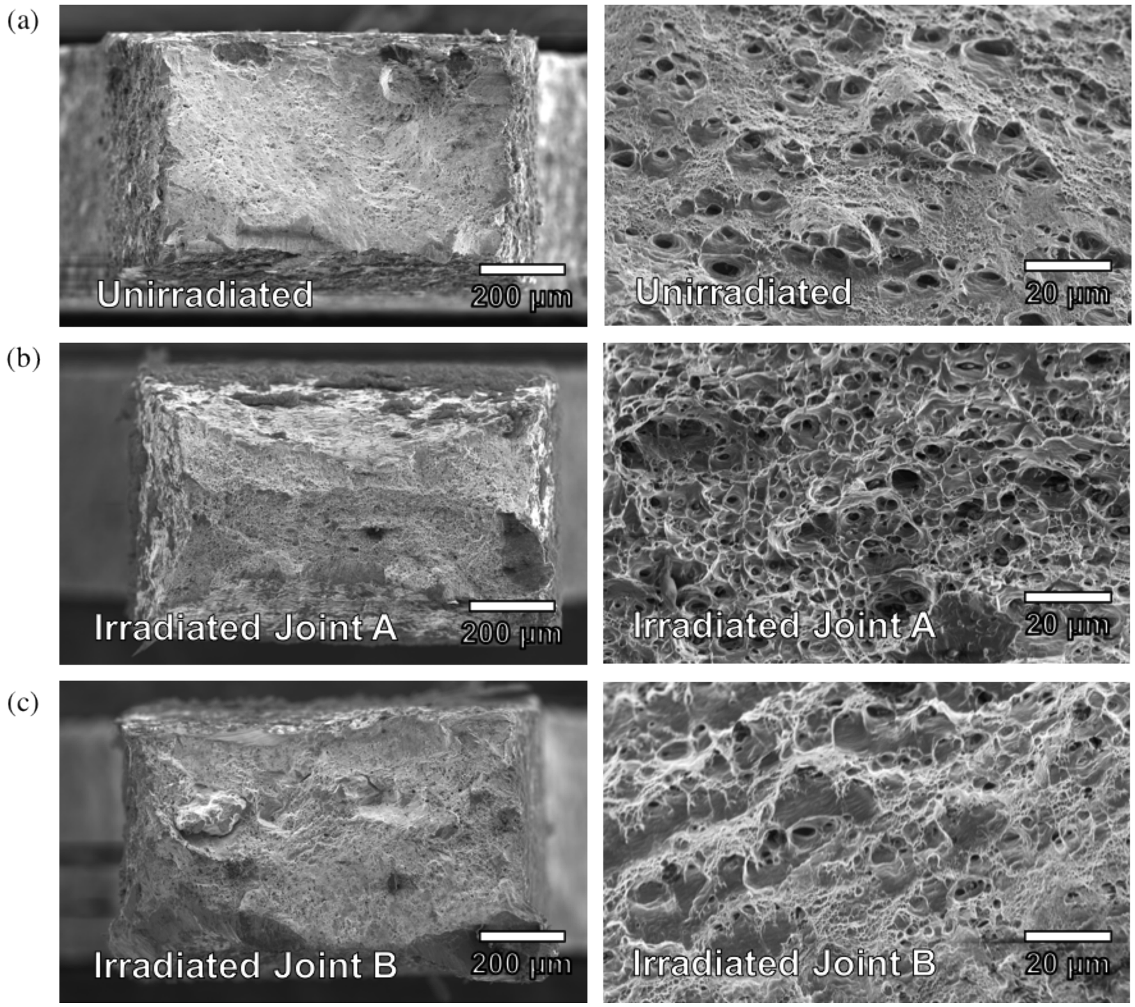

Fig. 3: SEM micrographs showing the fracture surfaces in low magnification (left) and high magnification (right) after tensile testing in the (a) unirradiated control specimen (b) irradiated condition for Joint A and (c) irradiated condition for Joint B.

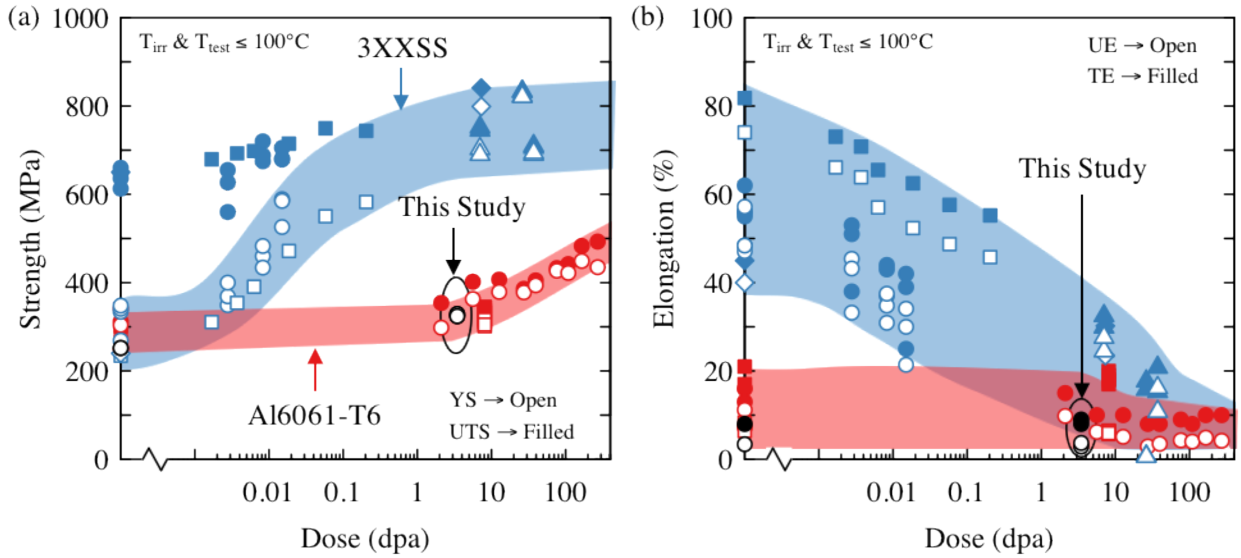

Fig. 4: Irradiation hardening and embrittlement values for bulk 300-series stainless steels in the annealed condition (blue symbols/polygons), and for Al6061-T6 (red symbols/polygons), neutron-irradiated and tensile-tested at or below 100°C. Black symbols represent values from this study. Literature for 300-series: ◯ [34], □ [35], ◇ [36], △ [37] and for Al: ◯ [38], □ [39]. For more extensive databases, see Ref. [40] for Al6061-T6 and Ref. [41] for 300-series stainless steels; neither could be digitized because of poor digital reproduction.